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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the status of development, under DURIP grant number F49620-96-1-0390, of a new *in situ*, UHV low temperature Ballistic Electron Emission Microscope (BEEM) for study of localized transport through metal semiconductor heterostructures. The apparatus has been developed as planned in phases. Phase I, which involves the development of UHV BEEM capability at room temperature, is fully functional at UCSB, and is yielding excellent BEEM imaging data. Phase II, which involves low temperature operation (Liquid N_2) is also installed at UCSB and is in final stages of testing. Phase III, which involves an *in situ* evaporation chamber, is in final stages of assembly at Surface/Interface Inc.

The UHV BEEM data already show that this will provide a unique materials characterization capability for electronic materials researchers at UCSB.

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In-Situ UHV Low Temperature Ballistic-Electron-Emission Microscope for nm-Scale Imaging and Spectroscopy of Novel Compound Semiconductor Materials

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Ballistic Electron Emission Microscopy (BEEM) and Ballistic Electron Emission Spectroscopy (BEES) are powerful three terminal transport techniques for characterizing the surface and buried interfaces in semiconductor heterostructures over microscopic length scales [1-5]. In one variation of the approach, the semiconductor structure of interest is grown epitaxially on a conducting (semiconductor) substrate and then covered with a thin layer (~10nm) of a metal which serves as the base contact in a three terminal measurement. The sharp metal tip of a Scanning Tunneling Microscope (STM) is brought to within a few Angstroms of the metal layer such that, at a given electrical bias between the tip and the metal layer, a tunneling current is established across the vacuum gap between the emitter (tip) and the base (metal).

A fraction of the injected electrons traverse ballistically across the metal layer and reach the metal-semiconductor interface. When the electron energy is sufficiently large to overcome the Schottky barrier at this interface, there is electron transmission and the transmitted electrons are collected as the 'BEEM current' via the collector contact at the substrate, provided that further barriers do no occur between the metal-semiconductor interface and the substrate. If additional barriers do occur between the metal-semiconductor interface and the substrate, then electron transmission and, therefore, the BEEM current, becomes appreciable only when the electron energy is sufficiently large to overcome these barriers (in a quasi-classical description) [1]. As the energy distribution of the tip-injected electrons may be simply varied by ramping the electrical bias (VT) between the tip and the metal film, one may also carry out spectroscopy (BEES) by measuring the BEEM current as a function of the tip-metal bias; this allows for a characterization of potential barriers within the semiconductor heterostructure in a way that does not require the application of external biases across the semiconducting device.

In addition, due to the scanning capability of the instrument, one can obtain simultaneous STM and BEEM current images at various fixed electron energy distributions (i.e., constant VT). This capability allows for a study of correlation between variations in surface topography and changes in the internal potential profile over a microscopic length scale.

BEEM and BEES have thus far been successfully applied to various systems to study, for example, band offsets in semiconductor heterostructures, surface Schottky barriers, and defect

induced modifications of the electronic band structure [1-5]. Although the standard experiment has provided much useful information, it has been quite clear that further advances in this field, especially as it relates to the study of III-V semiconductors, will require better characterized interfaces prepared in a cleaner environment. One can appreciate this point upon examining Figure 1, where one sees that exposure of the epitaxially grown semiconductor to the ambient atmosphere before deposition of the metal layer can result in an oxide layer and/or adsorbed layer between the metal and the semiconductor. Such an uncharacterized interfacial layer might constitute an additional barrier that reduces the BEEM current at a given bias and change the relative contributions of the BEEM current attributable to the various bands in the semiconductor due to interchannel scattering.

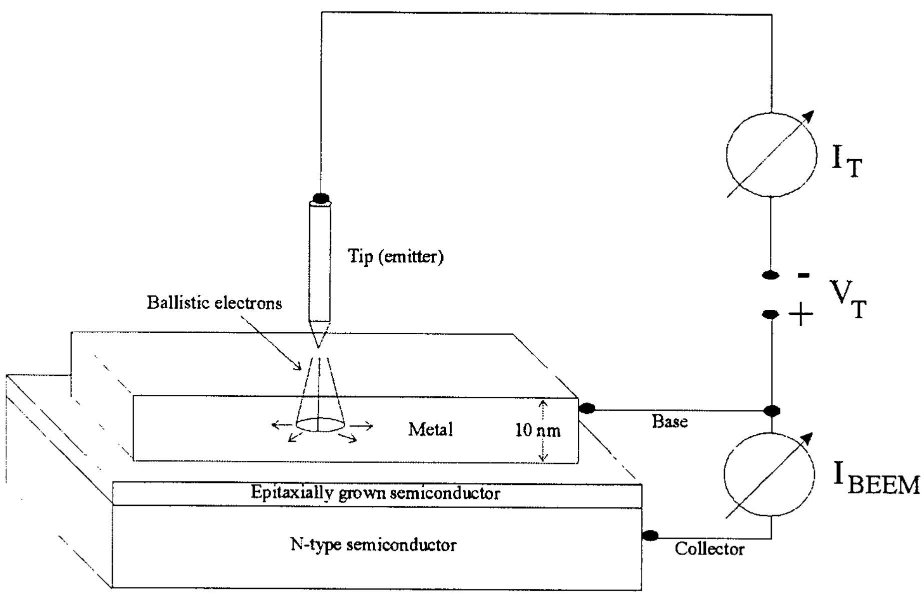


Figure 1) Ballistic Electron Emission Microscopy (BEEM) and Ballistic Electron Emission Spectroscopy (BEES) are carried out using a modified Scanning Tunneling Microscope (STM) that makes possible a three terminal measurement.

The deposition of the metal in a poorly controlled environment would also affect BEEM/BEES studies because impurities incorporated into the metal layer at the deposition stage would modify the electron mean free path in the metal. As the fraction of the injected electrons that are transmitted ballistically to the metal-semiconductor interface depends exponentially on this parameter, inadequate control of this parameter could result in sample to sample variations in the BEEM current (at fixed bias and tunneling current) that would preclude a quantitative data analysis.

Finally, exposure of the metal surface of the metal-semiconductor structure to atmosphere could result in an oxide/adsorbed layer atop the metal that would also complicate data analysis. (Here, it is worth noting that BEEM studies of specimens including some interesting metals such as aluminum are not possible after exposure to atmosphere because it is highly unstable towards

oxide formation.) In addition, BEEM measurements carried out under ambient conditions are also prone to poorly understood tip-surface interactions that are possibly mediated by constituents in the atmosphere. This feature has limited the utility of this technique at high biases, where one might probe the role of higher bands and one hopes to observe higher BEEM current.

The problems listed above identify the desirability of improving the standard experiment by eliminating these uncontrolled influences of impurities and the ambient environment. Indeed, one sees that most of these problems might be simply eliminated by taking a specimen from the sample preparation phase to the measurement phase in a clean and controlled environment. Thus, we are constructing a facility that allows for metal deposition and BEEM/BEES measurements in a clean ultra high vacuum environment and report on its progress here.

The UHV BEEM/BEES system at UCSB (see Fig. 2) consists of a load lock for introducing epitaxially grown semiconductors, a chamber for UHV electron beam evaporation of various metals, and a measurement chamber for carrying out BEEM/BEES studies to liquid nitrogen temperatures [6]. A magnetically coupled sample transfer arm is used to move the specimen from one chamber to the next so that sample preparation and measurement may be carried out without specimen exposure to atmosphere. A heater is also incorporated into the load lock in order to desorb surface oxides on the semiconductor structure prior to metal deposition.

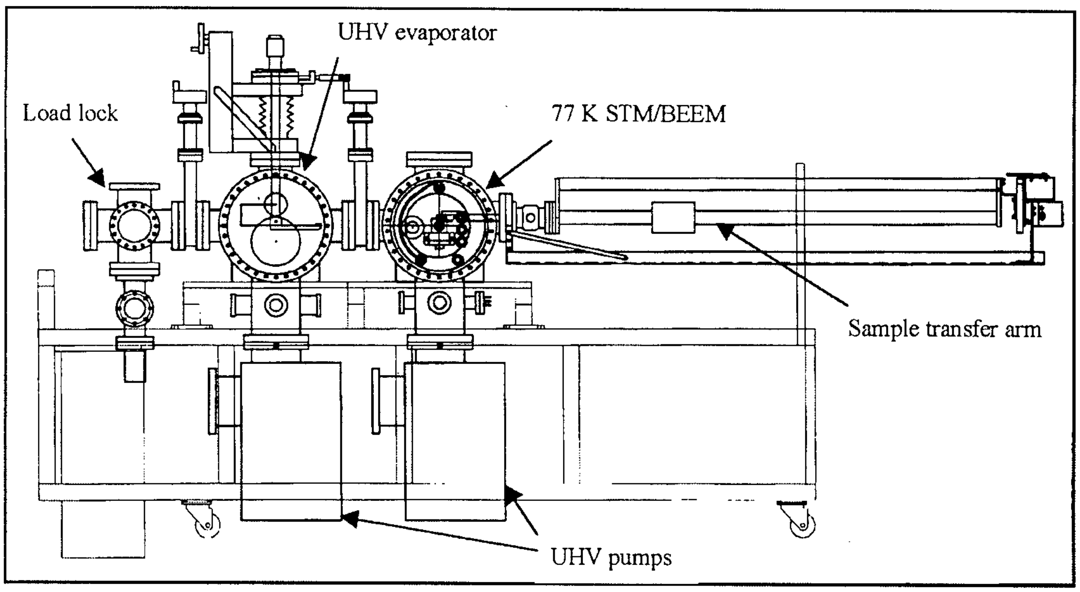


Figure 2) The planned ultra high vacuum BEEM/BEES system at UCSB. The setup includes a load lock for introducing epitaxially grown semiconductors, a UHV evaporator for depositing various metal layers, and a cryogenically cooled STM for BEEM and BEES.

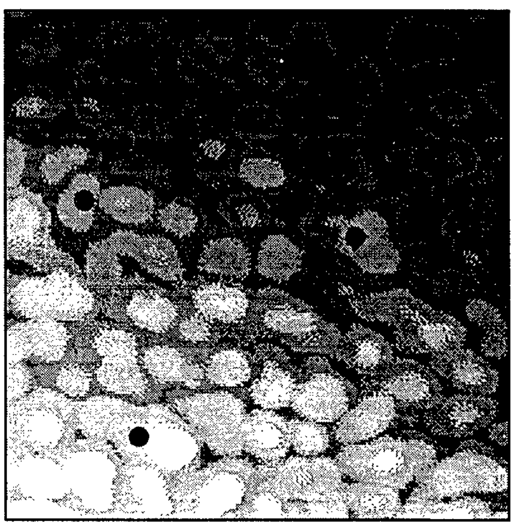
Construction and assembly of this system was planned to occur in three phases: The first phase includes the construction of the BEEM chamber, the load lock, and the sample transfer arm with associated vacuum pumps. The second phase includes the construction of the liquid nitrogen reservoir and associated thermal shields, and their incorporation into the existing apparatus. The

third phase includes the construction of the UHV evaporator assembly and its incorporation into the earlier phases. The apparatus connected with Phase I was delivered in April 1997 and the design for Phases II and III was completed in May 1997. Phase II was delivered to UCSB in October 1997 and is currently under test at UCSB. The Phase III evaporation chamber has been recently completed at Surface/Interface Inc. and installation is expected to be completed shortly.

Some typical experimental results obtained with the apparatus at the end of phase one will be shown here to demonstrate the capability of the system. It should be noted that the specimens used in these studies included metal layers which were deposited in an electron beam evaporator after the semiconductor surface was passivated in atmosphere. In addition, after metal deposition, the specimens were exposed once again to atmosphere while being transported to the measurement setup.

Figure 3 shows relatively large area STM scans of a 70Å gold layer on a GaAs epilayer grown atop a conducting GaAs substrate. The measurements were carried out at 300K with a bias voltage of 2V and a tunneling current of 2nA. These scans exhibit the granular structure of gold films deposited on a substrate at room temperature and, from the figure, one sees that the system exhibits excellent reproducibility in imaging over periods of hours.

UHV058; 52097; 2V; 2nA; 2000Ax2000A



UHV062; 52097; 2V, 2nA; 2000Ax2000A

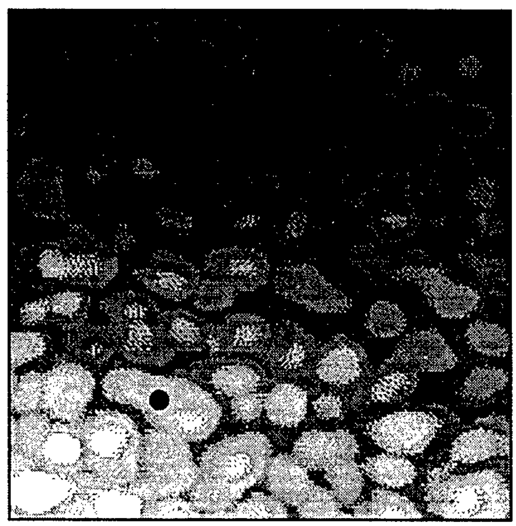


Figure 3) STM images of a 70 A gold layer on GaAs. These two images are scans of the same part of the specimen taken with a time interval of one-half hour. The colored dots are markers of identifying features that may be used to gauge the drift of the instrument. The irregular structures seen in these (2000A x 2000A) images are gold grains whose size depends on metal deposition temperature.

Similar results have also been obtained for smaller area scans (see Fig. 4) although, in this case, there is a perceptible change in the image due to a drift of the sample with respect to the tip in

the time interval between the images. Measurements indicate that the drift can be as large as several hundred Angstroms per hour.

UHV070; 52097; 2V; 2nA; 500Ax500A

UHV074; 52097; 2V; 2nA; 500Ax500A

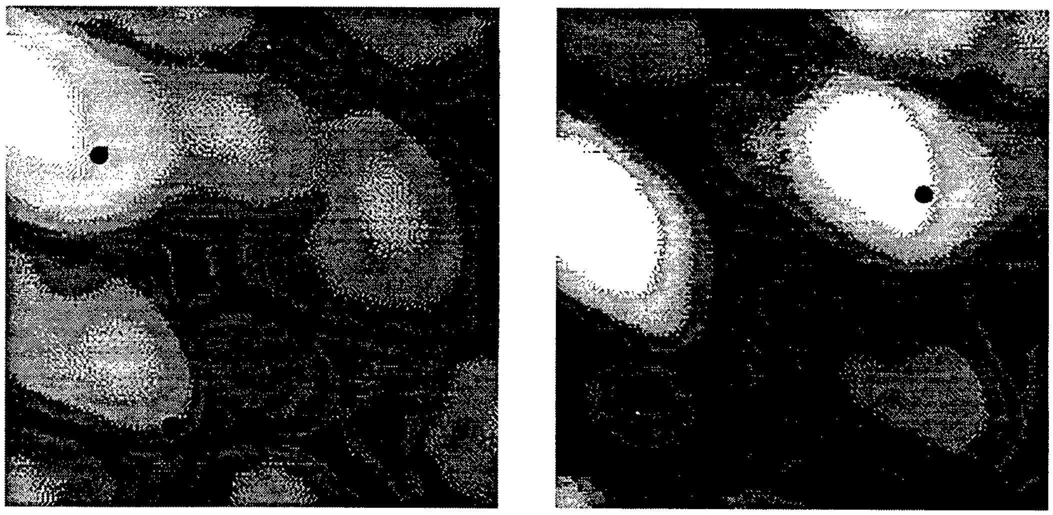


Figure 4) A pair of STM scans of 70A thick gold layer on GaAs, under nominally identical conditions. The colored dots mark the corresponding features in the two images. One sees the effect of thermal drift of sample with respect to the tip in these images. Scan field size is 500Ax500A.

In Figure 5, there is shown an STM image and the corresponding BEEM image (taken simultaneously) of the 70 Å gold layer on GaAs specimen examined in Figs. 3 and 4. Here, at fixed bias and tunneling current, the STM tip is scanned across a 500Åx500Å field on the specimen, and the surface height , i.e., the STM image, and BEEM current are measured at each point on a square grid in order to constuct the images shown in the figure. The striking feature here is low level of noise observed in the BEEM image although the BEEM current at each pixel is at the pico-ampere level. From the figure, one also observes that the BEEM image contrast at the grain boundaries (examine, for example, the contrast in the vicinity of the colored dots) can even be superior to that observed in the STM image. This feature suggests that buried defects near the surface of semiconductor devices might be imaged and studied successfully with this particular instrument.

Although data shown thus far have been for gold layers on GaAs, similar quality results may also be obtained for other metals on this semiconductor system. We illustrate this point by exhibiting some STM data for a 30Å platinum layer on a similar GaAs specimen (see Fig. 6). Here, the Pt metal layer thickness is smaller than that for the gold specimen because one expects greater attenuation of the BEEM current in the case of platinum, for the same metal layer thickness, due to the smaller electron mean free path in this metal. Then, one attempts to recover the desired magnitude of the BEEM signal by reducing the metal layer thickness. From the STM images

shown in Fig. 6, one notices that platinum films exhibit a granular structure just as in the case of gold films, although the structure here seems a bit more regular than in the former case.

UHV078; 52097; 2nA; 500Ax500A, STM

UHV077f; 52097; 2nA; 500Ax500A; BEEM

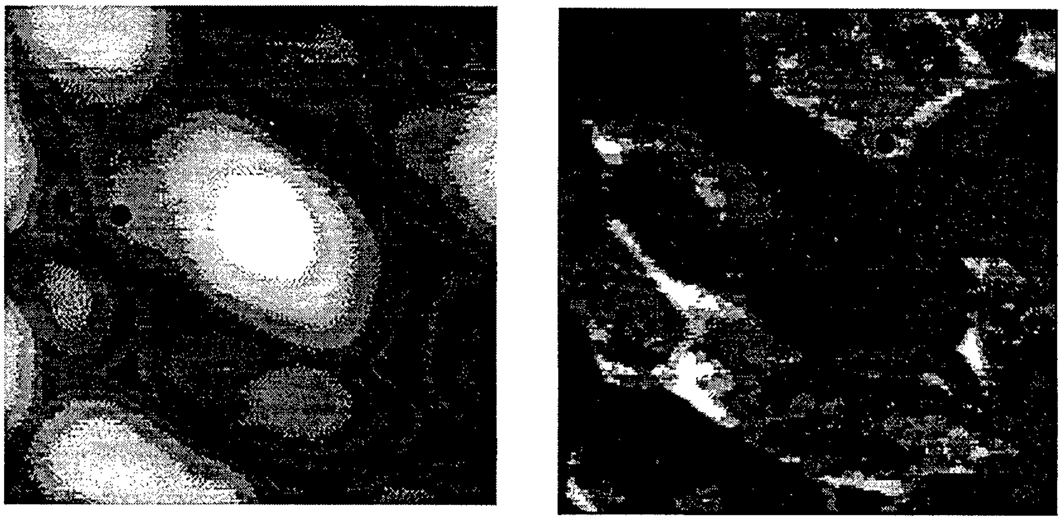


Figure 5) STM (left) and corresponding BEEM (right) images of a 70A gold-on-GaAs specimen. The image scan size is 500Ax500A. Note that the grain boundaries appear sharper in the BEEM image than the STM image in the vicinity of the colored dots. The tip to metal bias (2V) exceeds the Schottky barrier height in GaAs.

Al0pt009; 70797; 2V; 5nA; 1000Ax1000A

Al0pt013; 70797; 2V; 5nA; 1000Ax1000A

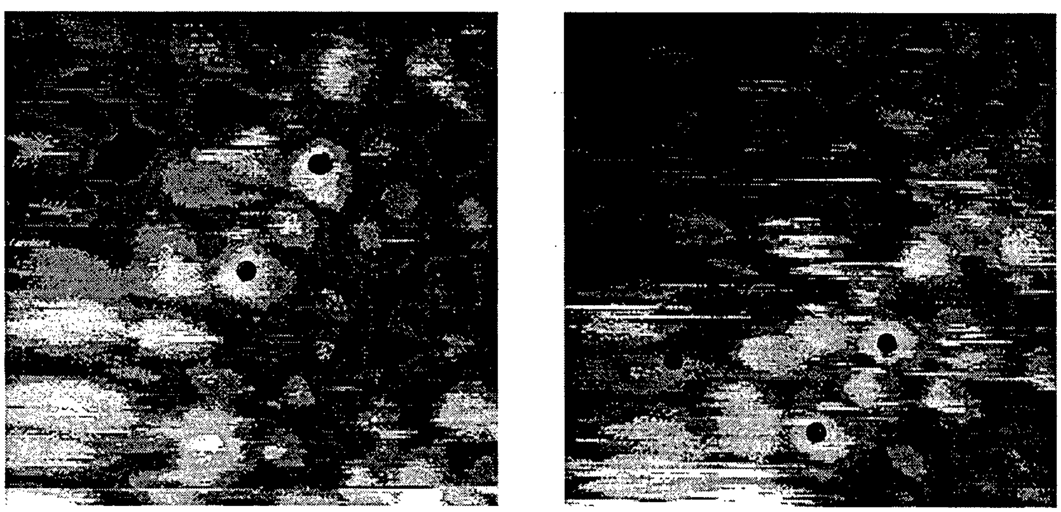


Figure 6) STM images of 30A platinum film on GaAs. The images, obtained nearly an hour apart, show excellent reproducibility once one accounts for thermal drifts which tends to shift the sample with respect to the STM tip.

In summary, studies to date have indicated that phase one of the UCSB UHV BEEM/BEES system performs to original specifications, as demonstrated by the data shown here. The liquid

nitrogen reservoirand assembly were installed in October and temperature monitoring and cycling are currently under test at UCSB. This capability will help improve signal to noise in BEES studies while reducing the overall thermal drifts within the system. Therefore, better imaging is expected at the end of phase two. Over the next few months, the UHV evaporator module will be added as part of phase three of the system upgrade. It is currently in final stages of test at Surface/Interface, Inc. This will then provide the capability to take a semiconductor specimen, desorb its surface oxide, deposit a clean metal film under UHV conditions, and subsequently perform BEEM/BEES measurements on it, without ever exposing the specimen to atmosphere. There is no doubt that, in the future, this state of the art experimental setup will provide novel insight into surface Schottky barriers and buried interfaces in a wide variety of epitaxially grown III-V semiconductor systems.

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